

HEPHY-PUB 624/95

UWThPh-1995-9

June 1995

# *CP*-violating asymmetries in top-quark production and decay in $e^+e^-$ annihilation within the MSSM

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## ABSTRACT

We obtain analytic formulae for the cross section of the sequential processes of  $e^+e^- \rightarrow t\bar{t}$  and  $t \rightarrow bl^+\nu / \bar{t} \rightarrow \bar{b}l^-\bar{\nu}$  in the laboratory frame, where the dependence on triple product correlations of the type  $(\hat{\mathbf{q}}_1 \times \hat{\mathbf{q}}_2 \cdot \hat{\mathbf{q}}_3)$ , induced by *CP* violation both in the production and the decay are explicitly shown. Different observables sensitive to *CP* violation are defined and calculated in the Minimal Supersymmetric Standard Model (MSSM). The observables sensitive to *CP* violation are of the order of  $10^{-3}$ . The dependence on the masses of the supersymmetric particles is also shown.

# 1. Introduction

Precision measurements of various production and decay modes of the top quark are expected to provide also information about physics beyond the Standard Model (SM). Testing new physics in observables which are sensitive to  $CP$  violation seems especially promising. As the top quark does not mix with other generations, the GIM mechanism of unitarity constraints leads to negligibly small effects of  $CP$  violation in the SM. Thus, observation of  $CP$  noninvariance in top-quark physics would definitely be a signal for physics beyond the SM [1, 2, 3, 4, 5].

Here we shall consider  $CP$  violation induced by supersymmetry (SUSY). In the Minimal Supersymmetric Standard Model (MSSM) [6], there are more possibilities to introduce complex couplings than in the SM. Even without generation mixing, nonzero complex phases can occur in the Lagrangian that cannot be rotated away by a suitable redefinition of the fields. They give rise to  $CP$  violation within a single generation, free of the unitarity suppression of the GIM mechanism.

In top-quark production and decay  $CP$  violation is due to radiative corrections. The magnitude is determined by the ratio of the masses of the top quark and the SUSY particles in the loop. Having in mind the large top-quark mass,  $m_t = 175\text{GeV}$  [7], we may expect that the  $CP$ -violating effects are only moderately suppressed. Thus, testing SUSY through  $CP$ -violating observables in top-quark physics is a promising task for future colliders.

Here, as possible evidence of  $CP$  violation we consider  $T$ -odd triple product correlations of the type

$$(\mathbf{q}_1 \mathbf{q}_2 \mathbf{q}_3) \equiv (\mathbf{q}_1 \times \mathbf{q}_2 \cdot \mathbf{q}_3) \quad (1)$$

where  $\mathbf{q}_{1,2,3}$  can be any one of the 3-momenta in  $e^+e^- \rightarrow t\bar{t}$  or of the  $t$  ( $\bar{t}$ )-decay products  $t \rightarrow b l^+ \nu$  ( $\bar{t} \rightarrow \bar{b} l^- \bar{\nu}$ ). This method has been proposed in [1, 2] for a general study of  $CP$  violation in  $t\bar{t}$  production in  $e^+e^-$  annihilation and in  $pp$  collisions. The correlations (1) are called  $T$ -odd as they change sign under a flip of the 3-momenta involved. However, this does neither imply time-reversal noninvariance nor  $CP$  violation if  $CPT$  is assumed. When loop corrections are included,  $T$ -odd correlations can arise either from absorptive parts in the amplitude (so-called final state interactions [8]), or from  $CP$  violation. The former effect is a consequence of the unitarity of the  $S$ -matrix, and it can be eliminated either by taking the difference between the process we are interested in and its  $CP$  conjugate [9] or

by direct estimates.  $T$ -odd correlations in the SM due to gluon or Higgs boson exchange in the final states have recently been considered in [10].

Note that in collider experiments top-antitop quark pairs will be copiously produced and the decay modes  $t \rightarrow bl^+\nu$  and  $\bar{t} \rightarrow \bar{b}l^-\bar{\nu}$  will occur simultaneously. Therefore, it will be possible to form the difference between the two conjugate processes in the same experiment.

The appearance of triple product correlations of the type (1) can also be explained by the fact that the top-quark polarization has non-vanishing transverse components both in the production plane and perpendicular to it. Because of the large mass of the top quark the produced  $t$  and  $\bar{t}$  can be regarded as free quarks with definite momenta and polarizations that are not affected by hadronization. Thus their polarization state can be inferred from the distribution of their decay products.

In the  $t\bar{t}$  production process

$$e^+(q_l) + e^-(q_l) \rightarrow t(p_t) + \bar{t}(p_{\bar{t}}), \quad (2)$$

a  $T$ -odd correlation in the c.m.system is  $(\xi \mathbf{q}_l \mathbf{p}_t)$  [3], where  $\xi$  is the top-quark polarization vector. Evidently, this correlation is different from zero only if  $\xi$  has a component *normal to the production plane*.

In the semileptonic  $t$  and  $\bar{t}$  decays:

$$t \rightarrow b(p_b)l^+(p_{l^+})\nu(p_\nu) \quad (3)$$

$$\bar{t} \rightarrow \bar{b}(p_{\bar{b}})l^-(p_{l^-})\bar{\nu}(p_{\bar{\nu}}) \quad (4)$$

a triple product correlation in the rest frame of the top quark is  $(\xi \mathbf{p}_b \mathbf{p}_{l^+})$  [4]. Here it is the polarization of the top quark *normal to the decay plane* that contributes. In the production as well as in the decay we shall only consider correlations due to  $CP$  violation.

As the polarization of the top quark is not a directly observable quantity, we obtain information about the above spin-momenta correlations by triple product correlations of type (1) among the 3-momenta of the particles in the sequential processes:

$$e^+ + e^- \rightarrow t + \bar{t} \rightarrow \bar{t} b l^+ \nu \quad (5)$$

$$e^+ + e^- \rightarrow t + \bar{t} \rightarrow t \bar{b} l^- \bar{\nu}. \quad (6)$$

In this paper we shall calculate the contribution to different triple product correlations of type (1) due to  $CP$  violation in (2) and in (3) or (4). We shall obtain analytic expressions for the sequential reactions (5) and (6) in which the triple product correlations (1), sensitive to  $CP$  violation in the production and in the decay, explicitly appear. The problem of distinguishing  $CP$  violation in  $t\bar{t}$  production and  $t$  decay was considered previously in [1]. We shall use the triple product correlations to investigate  $CP$  violation induced by SUSY. However, our method is completely general and can also be applied to study other sources of  $CP$  violation.

In section 2 we obtain general expressions of processes (5) and (6) using the formalism developed in [11]. We write them in a form in which  $CP$ -violation manifests itself in triple product correlations. In section 3 we obtain the expressions for the polarization vectors of the top and antitop quarks, when the electric and weak dipole-moment couplings are taken into account. Formulae for the cross section of (5) and (6) in the c.m.system with the explicit dependence on the triple products of type (1) are given in section 4. In section 5 we formulate the  $CP$  - violating observables. In section 6 we obtain numerical results for these effects in the MSSM.

## 2. The Cross Section

Here we obtain analytic expression for the cross section of the sequential processes (5) and (6), in terms of the top/antitop polarization vectors.  $CP$  violation in both the production and the  $t(\bar{t})$ -decay processes are taken into account.

We write the amplitudes of (5) and (6) in the form:

$$\begin{aligned} \mathcal{M}^{t,\bar{t}} = & \frac{g}{2\sqrt{2}} \bar{u}(p_\nu) \gamma_\alpha (1 \mp \gamma_5) u(-p_{l+}) \frac{-g^{\alpha\beta} + \frac{p_W^\alpha p_W^\beta}{m_W^2}}{p_W^2 - m_W^2 + im_W \Gamma_W} \\ & \times \bar{u}(p_b) V_\beta^{t,\bar{t}} \frac{\not{p}_t + m_t}{p_t^2 - m_t^2 + im_t \Gamma_t} A^{t,\bar{t}} u(-p_{\bar{t}}). \end{aligned} \quad (7)$$

Here  $A^{t,\bar{t}}$  enters the amplitude  $M$  for the production process (2) which we write in the two equivalent forms:

$$M = \bar{u}(p_t) A^t u(-p_{\bar{t}}) = \bar{u}_c(p_{\bar{t}}) A^{\bar{t}} u_c(-p_t). \quad (8)$$

$A^t$  and  $A^{\bar{t}}$  are given by s-channel  $\gamma$  and  $Z^0$  exchange,

$$A^{t,\bar{t}} = i \frac{e^2}{s} \bar{u}(-q_{\bar{t}}) \gamma_\alpha u(q_l) (\mathcal{V}_\gamma^{t,\bar{t}})^\alpha$$

$$-i \frac{g_Z^2}{s - m_Z^2} \bar{u}(-q_{\bar{l}}) \gamma_\alpha (c_V + c_A \gamma_5) u(q_l) (\mathcal{V}_Z^{t,\bar{t}})^\alpha, \quad (9)$$

where  $c_V = -1/2 + 2 \sin^2 \theta_W$ ,  $c_A = 1/2$  are the SM couplings of  $Z^0$  to the electron, and  $\sqrt{s}$  is the total c.m.energy. The quantities  $(\mathcal{V}_i^{t,\bar{t}})$  describe the  $t\bar{t}\gamma$  and  $t\bar{t}Z^0$  vertices:

$$\begin{aligned} (\mathcal{V}_\gamma^{t,\bar{t}})_\alpha &= \frac{2}{3} \gamma_\alpha \mp \frac{d^\gamma}{m_t} \mathcal{P}_\alpha \gamma_5, \\ (\mathcal{V}_Z^{t,\bar{t}})_\alpha &= \gamma_\alpha (g_V \pm g_A \gamma_5) \mp \frac{d^Z}{m_t} \mathcal{P}_\alpha \gamma_5, \end{aligned} \quad (10)$$

with  $\mathcal{P} = p_t - p_{\bar{t}}$ .  $g_V = 1/2 - 4/3 \sin^2 \theta_W$  and  $g_A = -1/2$  in eq. (10) are the SM top-quark couplings to the  $Z^0$ ,  $d^\gamma$  and  $d^Z$  are the electric and weak dipole moments of the  $t$ -quark, which in the limit of vanishing electron mass present the whole effect of  $CP$  violation. They can be induced only by  $CP$ -violating interaction and have in general both real and imaginary parts.

The  $t(\bar{t})$ -decays (3), (4) are treated as a sequence of the two-body decays  $t \rightarrow bW^+(p_W)$  and  $W^+ \rightarrow l^+ \nu$ , ( $\bar{t} \rightarrow \bar{b}W^-(p_W)$  and  $W^- \rightarrow l^- \bar{\nu}$ ). We write the  $tbW$  and  $\bar{t}\bar{b}W$  vertices in the form:

$$V_\alpha^t = \frac{g}{2\sqrt{2}} \left( \gamma_\alpha (1 - \gamma_5) + f_L^t \gamma_\alpha (1 - \gamma_5) + \frac{g_R^t}{m_W} P_\alpha^t (1 + \gamma_5) \right), \quad (11)$$

$$V_\alpha^{\bar{t}} = \frac{g}{2\sqrt{2}} \left( \gamma_\alpha (1 + \gamma_5) + f_L^{\bar{t}*} \gamma_\alpha (1 + \gamma_5) + \frac{g_R^{\bar{t}*}}{m_W} P_\alpha^{\bar{t}} (1 - \gamma_5) \right) \quad (12)$$

with  $g$  the weak coupling constant and  $P^t = p_t + p_b$ ,  $P^{\bar{t}} = p_{\bar{t}} + p_{\bar{b}}$ . In eqs. (11) and (12) we have kept only the terms that do not vanish in the approximation  $m_b = 0$ . The form factors  $f_L^{t,\bar{t}}$  and  $g_R^{t,\bar{t}}$  get contributions both from the  $CP$ -invariant absorptive parts of the amplitudes and from  $CP$ -violating interactions, and can have real and imaginary parts. Furthermore,  $CPT$  is assumed. Neglecting the absorptive parts we then have [1]:

$$f_L^t = (f_L^{\bar{t}})^* \equiv f_L, \quad g_R^t = (g_R^{\bar{t}})^* \equiv g_R \quad (13)$$

and  $CP$  invariance implies

$$f_L = f_L^*, \quad g_R = g_R^* \quad (14)$$

For the  $Wl\nu$ -vertices we take the SM tree level expressions.

The amplitude  $\mathcal{M}^{\bar{t}}$  for process (6) is obtained from (7) when also the spinors  $\bar{u}(p_\nu)$ ,  $u(-p_{l+})$ ,  $\bar{u}(p_b)$  and  $u(-p_{\bar{t}})$  are replaced by  $\bar{u}_c(p_{\bar{\nu}})$ ,  $u_c(-p_{l-})$ ,  $\bar{u}_c(p_{\bar{b}})$  and  $u_c(-p_t)$ , respectively, which describe the charge conjugate particles.

In order to obtain the general expression for the cross sections of (5) and (6) we use the formalism developed in [11].

In the narrow width approximation for the top and the  $W$  ( $\Gamma_t \ll m_t, \Gamma_W \ll m_W$ ) we obtain the cross section of reaction (5) in the form:

$$d\sigma = d\sigma_{e^+e^-} \cdot d\Gamma_{\bar{t}} \cdot \frac{p_{t_0}}{m_t \Gamma_t} \cdot d\Gamma_{\bar{W}} \frac{p_{W_0}}{m_W \Gamma_W}. \quad (15)$$

Here  $d\sigma_{e^+e^-}$  is the differential cross section for  $t\bar{t}$  production (2) in the c.m.s.,  $d\Gamma_{\bar{t}}$  is the decay rate for  $t \rightarrow bW$ , with the polarization state of the top quark determined in the production process  $e^+e^- \rightarrow t\bar{t}$ , and  $d\Gamma_{\bar{W}}$  is the partial decay rate of  $W \rightarrow l\nu$ , with the polarization state of the  $W$  determined in the preceding  $t$  decay.  $d\Gamma_{\bar{t}}$  and  $d\Gamma_{\bar{W}}$  are the decay distributions in the c.m.s. of the initial  $e^+e^-$ . As  $m_t \Gamma_t / p_{t_0}$  ( $m_W \Gamma_W / p_{W_0}$ ) is the total decay width of  $t$  ( $W$ ) in a frame in which the momentum of the top ( $W$ ) equals  $\mathbf{p}_t$  ( $\mathbf{p}_W$ ),  $d\Gamma_{\bar{t}} \cdot p_{t_0} / m_t \Gamma_t$  ( $d\Gamma_{\bar{W}} \cdot p_{W_0} / m_W \Gamma_W$ ) is the branching ratio of the decay  $t \rightarrow bW$  ( $W \rightarrow l\nu$ ) in the laboratory frame, with the polarization of  $t(W)$  determined in the preceding process.

Now we are interested only in triple product correlations in reactions (5) and (6) induced by  $CP$  violation in  $\mathcal{V}_\alpha^i$  and/or  $V_\alpha$ . First we consider process (5). Possible triple product correlations are  $(\mathbf{q}_l \mathbf{p}_t \mathbf{p}_b)$ ,  $(\mathbf{q}_l \mathbf{p}_t \mathbf{p}_{l+})$ ,  $(\mathbf{q}_l \mathbf{p}_{l+} \mathbf{p}_b)$ , and  $(\mathbf{p}_t \mathbf{p}_{l+} \mathbf{p}_b)$ . These correlations follow from the covariant quantities  $\varepsilon(p_1 p_2 p_3 p_4)$ , where  $p_i$  can be any one of the 4-vectors  $q_l$ ,  $q_{\bar{l}}$ ,  $p_t$ ,  $p_b$ ,  $p_{l+}$ , when written in the laboratory frame. (The symbol  $\varepsilon(p_1 p_2 p_3 p_4)$  means  $\varepsilon_{\alpha\beta\gamma\delta} p_1^\alpha p_2^\beta p_3^\gamma p_4^\delta$  with  $\varepsilon_{0123} = -1$ .)

The top-quark polarization normal to the production plane,  $\xi_N$ , which is induced by the  $CP$ -violating dipole couplings, gives rise to  $T$ -odd triple product correlations in  $e^+e^- \rightarrow t\bar{t}$  which are proportional to  $\Im m d^i$  [3].  $CP$ -violating triple product correlations in the decay  $t \rightarrow b l^+ \nu$  arise from the top polarization *transverse to the decay plane* and are induced by  $\Im m g_R$  in the  $tbW$ -vertex [4]. Both types of couplings  $d^i$  and  $g_R$  are generated by loop corrections.

We write the polarization 4-vector  $\xi^t$  and  $\xi^{\bar{t}}$  as the sum

$$\xi^{t,\bar{t}} = \xi_{SM}^{t,\bar{t}} + \xi_N^{t,\bar{t}}, \quad (16)$$

where  $\xi_{SM}$  is the tree level SM contribution that lies in the production plane, and  $\xi_N$  is the component normal to the production plane, which can arise in general

either from final-state interactions or from  $CP$ -violating interactions. Neglecting  $\Re g_R$  we obtain the following expression for the cross sections of (5) and (6) in terms of the top/antitop quark polarization vectors:

$$d\sigma^{t,\bar{t}} = \frac{96(4\pi)^2}{s} \alpha^2 \left( \frac{g}{2\sqrt{2}} \right)^4 (m_t^2 - 2(p_t p_{l^+})) N \{ A_{SM}^{t,\bar{t}} + A_d^{t,\bar{t}} + A_{g_R}^{t,\bar{t}} \} d\Gamma^{t,\bar{t}} \quad (17)$$

Here  $\alpha$  is the finestructure constant and

$$A_{SM}^{t,\bar{t}} = (p_t p_{l^+}) \mp m_t (\xi_{SM}^{t,\bar{t}} p_{l^+}), \quad (18)$$

$$A_d^{t,\bar{t}} = \mp m_t (\xi_N^{t,\bar{t}} p_{l^+}), \quad (19)$$

$$A_{g_R}^{t,\bar{t}} = \mp 2 \frac{\Im m g_R}{m_W} \varepsilon(\xi_{SM}^{t,\bar{t}} p_t p_{l^+} p_b), \quad (20)$$

$$N = \left( 1 + \beta^2 \cos^2 \theta \right) F_1 + \frac{4m_t^2}{s} F_2 + 2\beta \cos \theta F_3 \quad (21)$$

$$F_1 = \left( \frac{2}{3} \right)^2 + h_Z^2 (c_V^2 + c_A^2) (g_V^2 + g_A^2) - \frac{4}{3} h_Z c_V g_V$$

$$F_2 = \left( \frac{2}{3} \right)^2 + h_Z^2 (c_V^2 + c_A^2) (g_V^2 - g_A^2) - \frac{4}{3} h_Z c_V g_V$$

$$F_3 = 4h_Z c_A g_A \left( h_Z c_V g_V - \frac{1}{3} \right) \quad (22)$$

$A_{SM}^{t,\bar{t}}$  is the SM contribution with the first terms describing the contribution where the produced top and antitop are unpolarized, while the second one takes into account  $\xi_{SM}^{t,\bar{t}}$ .

The terms  $A_d^{t,\bar{t}}$  and  $A_{g_R}^{t,\bar{t}}$  contain the  $T$ -odd  $CP$ -violating correlations induced by  $\Im m d^\gamma$  and  $\Im m d^Z$  via  $\xi_N^{t,\bar{t}}$ , and by  $\Im m g_R$ , respectively. (Note that the form factor  $f_L$  of eqs.11 and 12 does not appear.) The complete expressions for  $\xi^{t,\bar{t}}$  will be given in the next section. The invariant phase space element  $d\Gamma$  is

$$d\Gamma^t = \frac{1}{(2\pi)^8} \delta(q_l + q_{\bar{l}} - p_{l^+} - p_\nu - p_b - p_{\bar{t}}) \cdot \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m_t^2) \\ \times \frac{\pi}{m_W \Gamma_W} \delta(p_W^2 - m_W^2) \frac{d\mathbf{p}_{l^+}}{2p_{l^+0}} \frac{d\mathbf{p}_\nu}{2p_{\nu 0}} \frac{d\mathbf{p}_b}{2p_{b0}} \frac{d\mathbf{p}_{\bar{t}}}{2p_{\bar{t}0}}. \quad (23)$$

Here  $\beta = \sqrt{1 - 4m_t^2/s}$  is the velocity factor of the  $t$ -quark in the c.m.system,  $\theta$  is the angle between the momenta of the initial electron and the  $t$ -quark, and

$$h_Z = \frac{s}{s - m_Z^2} \cdot \frac{g_Z^2}{e^2}, \quad g_Z = \frac{e}{\sin 2\theta_W}, \quad (24)$$

In order to obtain the cross section for reaction (6), in the expressions (17) – (20) and (23) the following replacements must be made:

$$p_t \rightarrow p_{\bar{t}}, \quad p_b \rightarrow p_{\bar{b}}, \quad p_{l+} \rightarrow p_{l-}, \quad p_\nu \rightarrow p_{\bar{\nu}}. \quad (25)$$

### 3. The top–quark polarization vector

First we calculate the polarization vector  $\xi_\alpha^t$  of the top quark. It is determined in the production process, and it is given by the expression [11]:

$$\begin{aligned} \xi_\alpha^t &= \left( g_{\alpha\beta} - \frac{p_{t\alpha} p_{t\beta}}{m_t^2} \right) \cdot \text{Tr} \left( A^t(-\Lambda(-p_{\bar{t}})) \bar{A}^t \Lambda(p_t) \gamma^\beta \gamma_5 \right) \\ &\times \left\{ \text{Tr} \left[ A^t(-\Lambda(-p_{\bar{t}})) \bar{A}^t \Lambda(p_t) \right] \right\}^{-1}. \end{aligned} \quad (26)$$

$\xi_\alpha^t$  can be decomposed along three vectors which are independent and orthogonal to  $p_t$ : two of them,  $Q_l$  and  $Q_{\bar{l}}$

$$Q_l = q_l - \frac{p_t q_l}{m_t^2} \cdot p_t \quad Q_{\bar{l}} = q_{\bar{l}} - \frac{p_t q_{\bar{l}}}{m_t^2} \cdot p_t \quad (27)$$

are in the production plane, and the third,  $\varepsilon^{\alpha\beta\gamma\delta} p_{t\beta} q_{l\gamma} q_{\bar{l}\delta}$ , is normal to it. We then have:

$$(\xi_{SM}^t)^\alpha = P_l^t(Q_l)^\alpha + P_{\bar{l}}^t(Q_{\bar{l}})^\alpha \quad (\xi_N^t)^\alpha = D^t \varepsilon^{\alpha\beta\gamma\delta} p_{t\beta} q_{l\gamma} q_{\bar{l}\delta}. \quad (28)$$

We neglect contributions of  $\Im m d^\gamma$  and  $\Im m d^Z$  to  $P_l^t$  and  $P_{\bar{l}}^t$  as they are much smaller than the SM contributions. Together with eqs. (9) and (10), up to first order in  $\Im m d^\gamma$  and  $\Im m d^Z$ , eq. (26) implies the following expressions for the three components of the polarization vector as defined above:

$$\begin{aligned} P_l^t &= \frac{2m_t}{s} \{ (1 - \beta \cos \theta) G_1 + (1 + \beta \cos \theta) G_2 \\ &\quad - (3 - \beta \cos \theta) G_3 \} / N, \end{aligned} \quad (29)$$

$$\begin{aligned} P_{\bar{l}}^t &= -\frac{2m_t}{s} \{ (1 + \beta \cos \theta) G_1 + (1 - \beta \cos \theta) G_2 \\ &\quad + (3 + \beta \cos \theta) G_3 \} / N, \end{aligned} \quad (30)$$

$$D^t = \frac{8}{sm_t} \{ D_1 + \beta \cos \theta D_2 \} / N. \quad (31)$$

Here

$$G_1 = 2h_Z^2 c_V c_A (g_V^2 + g_A^2) - \frac{4}{3} h_Z c_A g_V, \quad (32)$$



$$G_2 = 2h_Z^2 c_V c_A (g_V^2 - g_A^2) - \frac{4}{3} h_Z c_A g_V, \quad (33)$$

$$G_3 = 2h_Z^2 (c_V^2 + c_A^2) g_V g_A - \frac{4}{3} h_Z c_V g_A, \quad (34)$$

$$D_1 = 2h_Z^2 c_V c_A g_V \Im m d^Z - h_Z c_A \left( g_V \Im m d^\gamma + \frac{2}{3} \Im m d^Z \right), \quad (35)$$

$$D_2 = h_Z^2 (c_V^2 + c_A^2) g_A \Im m d^Z - h_Z c_V g_A \Im m d^\gamma \quad (36)$$

As can be seen from eqs. (28),(31),(36),(37),  $\Im m d^\gamma$  and  $\Im m d^Z$  enter only in the polarization component transverse to the production plane.

In an analogous way we write the polarization vector  $\xi_{SM}^{\bar{t}}$  of the antitop quark as

$$(\xi_{SM}^{\bar{t}})^\alpha = P_l^{\bar{t}} \bar{Q}_l^\alpha + P_l^{\bar{t}} \bar{Q}_l^\alpha, \quad (\xi_N^{\bar{t}})^\alpha = D^{\bar{t}} \varepsilon^{\alpha\beta\gamma\delta} p_{\bar{t}\beta} q_{l\gamma} q_{\bar{l}\delta}, \quad (37)$$

where

$$\bar{Q}_{l(\bar{l})} = Q_{l(\bar{l})}(p_t \rightarrow p_{\bar{t}}). \quad (38)$$

Then we obtain

$$P_l^{\bar{t}} = -P_l^t, \quad P_l^{\bar{t}} = -P_l^t, \quad D^{\bar{t}} = D^t. \quad (39)$$

In the c.m.system, the expressions (27) – (31) and (37) – (39) for  $\xi^{t,\bar{t}}$  lead to the following relations between the space components of the polarization vectors of the top and the antitop:

$$\vec{\xi}_{SM}^{\bar{t}} = \vec{\xi}_{SM}^t \quad (40)$$

$$\vec{\xi}_N^{\bar{t}} = -\vec{\xi}_N^t. \quad (41)$$

This result can be readily understood by applying the  $CP$  operator (and is also a check of our results):  $CP$  invariance implies  $\vec{\xi}^t = \vec{\xi}^{\bar{t}}$  which is nothing but the result (40) for the tree level SM (i. e.  $CP$  conserving) contribution. Evidently, eq. (41) violates  $CP$ , being induced by  $d^\gamma$  and  $d^Z$ .

Eq. (39) implies:

$$A_{SM}^{\bar{t}}(p_{\bar{t}}, p_{l^-}, p_{\bar{b}}) = A_{SM}^t(p_t, p_{l^+}, p_b), \quad (42)$$

$$A_d^{\bar{t}}(p_{\bar{t}}, p_{l^-}, p_{\bar{b}}) = -A_d^t(p_t, p_{l^+}, p_b), \quad (43)$$

$$A_{g_R}^{\bar{t}}(p_{\bar{t}}, p_{l^-}, p_{\bar{b}}) = -A_{g_R}^t(p_t, p_{l^+}, p_b). \quad (44)$$

## 4. Triple product correlations

Now we obtain the explicit dependence of the cross section of processes (5) and (6) on triple product correlations of type (1) in the c.m.system, the laboratory frame of the initial  $e^+e^-$  beams.

From (17), (26) and (37) we obtain the cross section  $d\sigma^{t,\bar{t}}$  in the c.m. system.

$$d\sigma^{t,\bar{t}} = \sigma_{SM}^{t,\bar{t}} \left\{ 1 + \frac{1}{1 - \beta(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_{l+})} \left[ (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_{l+}) A_1^{t,\bar{t}} + (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) A_2^{t,\bar{t}} \right. \right. \\ \left. \left. + (\hat{\mathbf{p}}_t \hat{\mathbf{p}}_{l+} \hat{\mathbf{p}}_b) A_3^{t,\bar{t}} + (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_{l+} \hat{\mathbf{p}}_b) A_4^{t,\bar{t}} \right] \right\} d\Omega_t d\Omega_b d\Omega_l \quad (45)$$

where  $\hat{q}_e, \hat{p}_t$ , etc. denote the corresponding unit 3-vectors.

We have

$$\sigma_{SM}^{t,\bar{t}} = \frac{\alpha^2}{4\pi^4} \left( \frac{g}{2\sqrt{2}} \right)^4 \frac{\beta [m_t^2 - 2(p_t p_{l+})]}{s m_t \Gamma_t m_W \Gamma_W} \frac{E_b^2}{m_t^2 - m_W^2} \frac{E_l^2}{m_W^2} N A_{SM}^{t,\bar{t}} \quad (46)$$

which is the expression for the SM cross sections of (5) and (6). Here  $E_b$  and  $E_l$  are the energies of the the b-quark and the final lepton in the c.m.s.

$$E_b = \frac{m_t^2 - m_W^2}{2E} \frac{1}{1 - \beta(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_b)} \quad (47)$$

$$E_l = \frac{m_W^2}{2[E(1 - \beta(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_{l+})) - E_b(1 - (\hat{\mathbf{p}}_b \hat{\mathbf{p}}_{l+}))]} \quad (48)$$

and  $E = \sqrt{s}/2$ . For the asymmetries  $A_i$  we obtain:

$$A_1^{t,\bar{t}} = \mp \beta \left[ \frac{D}{2} - \frac{m_t}{\sqrt{s}} E_b P_- \frac{\Im m g_R}{m_W} \right] \quad (49)$$

$$A_2^{t,\bar{t}} = \mp \beta \frac{m_t}{\sqrt{s}} E_b P_- \frac{\Im m g_R}{m_W} \quad (50)$$

$$A_3^{t,\bar{t}} = - \beta \frac{m_t}{\sqrt{s}} E_b P_+ \frac{\Im m g_R}{m_W} \quad (51)$$

$$A_4^{t,\bar{t}} = \pm \frac{m_t}{\sqrt{s}} E_b P_- \frac{\Im m g_R}{m_W} \quad (52)$$

where

$$P_- = \frac{4}{N} [G_1 + G_2 + \beta \cos \theta G_3] \\ P_+ = -\frac{4}{N} [3G_3 + \beta \cos \theta (G_1 - G_2)] \\ D = \frac{8}{N} [D_1 + \beta \cos \theta D_2] , \quad (53)$$

$N$  was defined in eq.(21).

In order to obtain the expressions (45) – (52) for the reaction (6) (with the upper index  $\bar{t}$ ) also the replacements (25) have to be made.

Notice, that only the correlation  $(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l)$  gets a CP violating contribution from both the production and the decay, whereas the other correlations are sensitive only to CP violation in the decay. From eqs. (49) – (52) one expects that the triple product correlations discussed above are less sensitive to  $CP$  violation in top–decay than in  $t\bar{t}$  production, because  $\Im mg_R$  is multiplied by the SM–polarization  $P_\pm$  and by  $E_b/\sqrt{s}$ .

We want to remark that  $(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l)$ ,  $(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b)$  and  $(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b)$  do not change sign under the replacements (25) when calculating  $d\sigma^{\bar{t}}$  in the c.m.s., while  $(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b)$  changes sign. Together with eqs. (49)–(52) this implies that a nonzero value of the difference of  $d\sigma^t$  and  $d\sigma^{\bar{t}}$  would be the genuine signal for a triple product correlation induced by  $CP$  violation.

## 5. Observables

We consider two types of observables:

(i) If  $N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) > 0 (< 0)]$  is the number of events in which  $(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) > 0 (< 0)$ , with analogous definitions for the other triple products, we define the following  $T$ –odd asymmetries:

$$O_1 = \frac{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) > 0] - N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) < 0]}{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) > 0] + N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) < 0]} \quad (54)$$

$$O_2 = \frac{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) > 0] - N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) < 0]}{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) > 0] + N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) < 0]} \quad (55)$$

$$O_3 = \frac{N[(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) > 0] - N[(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) < 0]}{N[(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) > 0] + N[(\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) < 0]} \quad (56)$$

$$O_4 = \frac{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) > 0] - N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) < 0]}{N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) > 0] + N[(\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) < 0]} \quad (57)$$

(ii) The other  $T$ –odd observables we consider are the mean values of the triple product correlations:

$$M_1 = \langle (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_l) \rangle \quad (58)$$

$$M_2 = \langle (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_t \hat{\mathbf{p}}_b) \rangle \quad (59)$$

$$M_3 = \langle (\hat{\mathbf{p}}_t \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) \rangle \quad (60)$$

$$M_4 = \langle (\hat{\mathbf{q}}_l \hat{\mathbf{p}}_l \hat{\mathbf{p}}_b) \rangle \quad (61)$$

The truly  $CP$ -violating effect would be a nonzero value of the differences:

$$\mathcal{O}_i = O_i - \bar{O}_i \quad (62)$$

$$\mathcal{M}_i = M_i - \bar{M}_i \quad (63)$$

where  $O_i$  and  $M_i$  refer to (5) and  $\bar{O}_i$  and  $\bar{M}_i$  refer to reaction (6).

Some of these correlations ( $\mathcal{M}_1$  and  $\mathcal{M}_4$ ) have been considered previously in [1]

## 6. Minimal Supersymmetric Standard Model

In this section we shall give numerical predictions in the MSSM [6] for the observables defined in the preceding section as well as for the quantities  $d^\gamma$ ,  $d^Z$ ,  $\Im mg_R$ , and  $\xi_N^{t,\tilde{t}}$ .

The SM contribution is too small to be of any interest to be measured. Due to flavour mixing of the three generations of quarks  $d^i$  is a two-loop effect. The contribution to  $\Im mg_R$  has been estimated in [12].

In the MSSM  $d^\gamma$ ,  $d^Z$  and  $\Im mg_R$  are generated at one-loop order, irrespectively of generation mixing. The main contribution comes from diagrams with gluino and scalar quarks in the loop, as shown in Fig. 1. The  $CP$ -violating phases  $\phi_A$  and  $\phi_{\tilde{g}}$  appear in the stop-squark mixing matrix and in the Majorana mass term of the gluino, respectively [13].

The dipole moments are determined by the gluino – stop exchange loops in the  $t\bar{t}\gamma$  and  $t\bar{t}Z^0$  vertices (see Fig. 1) and are given by the following expressions:

$$\frac{d^\gamma}{m_t} = \frac{\alpha_s}{3\pi} \frac{2}{3} \tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) [I_{11} - I_{22} - 2(I'_{11} - I'_{22})] \quad (64)$$

$$\begin{aligned} \frac{d^Z}{m_t} &= \frac{\alpha_s}{3\pi} \tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) \sum_n \left( |a_n^L|^2 - \frac{4}{3} \sin^2 \theta_W \right) \\ &\times [I_{1n} - I_{2n} - 2(I'_{1n} - I'_{2n})] \end{aligned} \quad (65)$$

The  $CP$ -violating phases enter only in the combination  $\phi_A - \phi_{\tilde{g}}$ .  $\tilde{\theta}$  is the stop – mixing angle which transforms the stop mass eigenstates  $\tilde{t}_n$ ,  $n = 1, 2$ , with masses  $m_{\tilde{t}_n}$ , to the weak eigenstates  $\tilde{t}_L$  and  $\tilde{t}_R$ :

$$\tilde{t}_L = \exp(-i\phi_A/2) (\cos \tilde{\theta} \tilde{t}_1 + \sin \tilde{\theta} \tilde{t}_2) \equiv a_n^L \cdot \tilde{t}_n \quad (66)$$

$$\tilde{t}_R = \exp(i\phi_A/2) (-\sin \tilde{\theta} \tilde{t}_1 + \cos \tilde{\theta} \tilde{t}_2) \equiv a_n^R \cdot \tilde{t}_n. \quad (67)$$

We have also used the notation:

$$I_{n,m} = \int \frac{d^4k}{\pi^2} \frac{1}{k^2 - \tilde{m}_g^2} \frac{1}{(p_t - k)^2 - \tilde{m}_n^2} \frac{1}{(p_{\bar{t}} + k)^2 - \tilde{m}_m^2} \quad (68)$$

$$\mathcal{P}_\alpha I'_{n,m} + \mathcal{Q}_\alpha I''_{n,m} = \int \frac{d^4k}{\pi^2} k_\alpha \frac{1}{k^2 - \tilde{m}_g^2} \frac{1}{(p_t - k)^2 - \tilde{m}_n^2} \frac{1}{(p_{\bar{t}} + k)^2 - \tilde{m}_m^2} \quad (69)$$

where  $\mathcal{Q} = p_t + p_{\bar{t}}$  and  $\tilde{m}_n \equiv m_{\tilde{t}_n}$ ,  $m, n = 1, 2$ .

The  $CP$ -violating contribution to  $\Im m g_R$  from the gluino-stop-sbottom loop (see Fig.1) reads:

$$\frac{\Im m g_R}{m_W} = -\frac{\alpha_s}{3\pi} \tilde{m}_g \sin 2\tilde{\theta} \sin(\phi_A - \phi_{\tilde{g}}) [I_1 - I_2 - 2(I'_1 - I'_2)] \quad (70)$$

Here  $I_n$  and  $I'_n$  are obtained from (68) and (69) by replacing  $p_{\bar{t}} \rightarrow -p_b$  and  $\tilde{m}_m \rightarrow m_{\tilde{b}_L}$ ,  $m_{\tilde{b}_L}$  being the  $\tilde{b}_L$  mass. In obtaining (70) we have neglected the mixing of the scalar-bottom eigenstates.

We have studied the dependence of  $\Im m d^\gamma$ ,  $\Im m d^Z$ ,  $\Im m g_R$ ,  $\xi_N^{t,\bar{t}}$  and the  $CP$  violating quantities  $O_i$  and  $M_i$  on  $\sqrt{s}$ , the top-quark mass  $m_t$ , and the SUSY parameters  $m_{\tilde{g}}$ ,  $m_{\tilde{t}_1}$  and  $m_{\tilde{b}_L}$ . In our numerical analysis we have assumed maximal mixing,  $\sin 2\tilde{\theta} = 1$ , and maximal  $CP$  -violation,  $\sin(\phi_A - \phi_{\tilde{g}}) = 1$ . In the presentation of our results we choose the following set of reference values:  $\sqrt{s} = 500$  GeV,  $m_t = 175$  GeV,  $m_{\tilde{g}} = 200$  GeV,  $m_{\tilde{t}_1} = 150$  GeV,  $m_{\tilde{t}_2} = 400$  GeV, and  $m_{\tilde{b}_L} = 200$  GeV. In the figures below we show the dependence of  $\Im m d^\gamma$ ,  $\Im m d^Z$ ,  $\Im m g_R$  and the quantities  $O_i$  and  $M_i$  on one of the parameters, with the other parameters being fixed at their reference values.

We first show in Figs. 2a, b, and c the dependence of the  $\Im m d^\gamma$  and  $\Im m d^Z$  on the beam energy  $\sqrt{s}$ , and on  $m_{\tilde{g}}$  and  $m_{\tilde{t}_1}$ , respectively. Typically they have values in the range  $10^{-3} - 10^{-2}$ .

Figs. 3a and b show the dependence of  $\Im m g_R$  on the SUSY parameters  $m_{\tilde{g}}$  and  $m_{\tilde{b}_L}$ . Roughly,  $\Im m g_R$  is an order of magnitude smaller than the dipole moments ( $\Im m g_R \approx 10^{-4} - 10^{-3}$ ). As can be seen, the dipole moments  $\Im m d^{\gamma,Z}$  and  $\Im m g_R$  exhibit a rather strong dependence on  $m_{\tilde{t}_1}$ , changing sign at  $m_{\tilde{t}_1} = 400$  GeV. ( For our particular set of chosen parameters  $m_{\tilde{t}_1} = 400$  GeV corresponds to  $m_{\tilde{t}_1} = m_{\tilde{t}_2}$ . At this point eqs. (64) and (70) immediately lead to  $\Im m d^\gamma = 0$  and  $\Im m g_R = 0$ ; eq. (65) implies  $\Im m d^Z = 0$ , but only for the considered case of maximal mixing. )

Figs. 4a, b, c and 5a, b, c exhibit the dependence of the  $CP$  - violating quantities  $M_i$ , and  $O_i$ ,  $i=1,\dots,4$ , on  $\sqrt{s}$ ,  $m_{\tilde{g}}$  and  $m_{\tilde{t}_1}$ . Note that the observables  $\mathcal{O}_i$  and  $\mathcal{M}_i$  as

defined in eqs. (62) and (63) are  $\mathcal{O}_i = 2O_i$  and  $\mathcal{M}_i = 2M_i$ . Above the threshold region and up to  $\sqrt{s} \approx 1$  TeV the  $M_i$  and the  $O_i$  are only weakly dependent on  $s$ .  $O_2$ ,  $O_4$  and  $M_4$  are the largest. Their values are of the order of  $10^{-3}$ . The dependence on  $m_{\tilde{g}}$  and  $m_{\tilde{t}_1}$  reflects the dependence of  $\Im m d^{\gamma, Z}$  and  $\Im m g_R$  on these parameters, changing sign at  $m_{\tilde{t}_1} = m_{\tilde{t}_2} = 400$  GeV.

## 7. Concluding remarks

Here we have considered  $T$ -odd triple product correlations and corresponding asymmetries for  $t\bar{t}$  production in  $e^+e^-$  annihilation with subsequent semileptonic decays of  $t$  or  $\bar{t}$ .

The contribution to the  $T$ -odd correlations induced by possible  $CP$ -violating interactions have been studied.  $T$ -odd  $CP$ -violating observables  $\mathcal{O}_i$ , eq. (62), and  $\mathcal{M}_i$ , eq. (63), have been defined. Numerical predictions within the MSSM have been given, and their dependence on the SUSY parameters and  $\sqrt{s}$  has been presented. Our analysis shows:

1. Above threshold there is only a weak dependence on  $\sqrt{s}$ . The quantities  $\mathcal{O}_2$ ,  $\mathcal{O}_4$  and  $\mathcal{M}_4$  are larger than the others. Their values at  $\sqrt{s} = 500$  GeV are of the order of  $10^{-3}$  for  $m_{\tilde{t}_1} \leq 200$  GeV and  $m_{\tilde{g}} \lesssim 500$  GeV. Note that the observables  $\mathcal{O}_4$  and  $\mathcal{M}_4$  have also the advantage that they involve only the momenta of the  $t$  and  $\bar{t}$  decay products.
2. There is a marked dependence on  $m_{\tilde{t}_1}$ . At  $m_{\tilde{t}_1} = m_{\tilde{t}_2}$  both  $\mathcal{O}_i$  and  $\mathcal{M}_i$  change sign.
3. The observables  $\mathcal{O}_i$  and  $\mathcal{M}_i$  considered exhibit less sensitivity to  $CP$  violation in top decay. This is due to the fact that i)  $\Im m g_R$  is smaller than  $d^{\gamma, Z}$ , and ii) the contribution of  $\Im m g_R$  to  $\mathcal{O}_i$  and  $\mathcal{M}_i$  is proportional to the degree of  $t(\bar{t})$  polarization induced by the SM.

## Acknowledgements

We thank Helmut Eberl for his constructive assistance in the evaluation of the loop integrals. E.C.'s work has been supported by the Bulgarian National Science Foundation, Grant Ph-16. This work was also supported by the 'Fonds zur Förderung der wissenschaftlichen Forschung' of Austria, project no. P10843 -PHY.

## References

- [1] W.Bernreuther, O.Nachtmann, P.Overmann, T.Schröder, *Nucl.Phys.* **388** (1992) 53  
W.Bernreuter, P.Overmann *Z.Phys.* **C61** (1994) 599
- [2] W.Bernreuther and O.Nachtmann, *Phys.Lett.* **B268** (1991) 424  
A.Brandenburg, J.P.Ma, R.Münch, O.Nachtmann, *Z.Phys.* **C51** (1991) 225  
W.Bernreuther and A.Brandenburg, *Phys.Lett.* **B314** (1993) 104; *Phys.Rev.* **D49** (1994) 4481
- [3] D.Atwood and A.Soni, *Phys.Rev.* **D45** (1992) 2405  
E.Christova and M.Fabbrichesi, *Phys.Lett.* **B315** (1993) 113
- [4] E.Christova and M.Fabbrichesi, *Phys.Lett.* **B315** (1993) 338
- [5] C.R.Schmidt and M.E.Peskin, *Phys.Rev.Lett.* **69** (1992) 410  
B.Grzadkowski and J.Gunion, *Phys.Lett.* **B287** (1992) 237  
C.R.Schmidt *Phys.Lett.* **B293** (1992) 111  
B.Grzadkowski, *Phys.Lett.***B305** (1993) 384; *Phys.Lett.***B316** (1993) 137  
B.Grzadkowski and W.Keung, *Phys.Lett.* **B319** (1993) 526  
E.Christova and M.Fabbrichesi, *Phys.Lett.* **320**(1994) 299
- [6] H.E.Haber and G.Kane, *Phys.Rep.* **117** (1985) 75  
J.Gunion and H.E.Haber, *Nucl.Phys.* **B272** (1986) 1
- [7] CDF Collaboration, F.Abe et al, *Phys.Rev.Lett.* **74** (1995) 2626  
D0 Collaboration, S. Abachi et al, *Phys.Rev.Lett.* **74** (1995) 2632
- [8] E.M.Henley and B.A.Jacobson, *Phys.Rev.Lett.***16** (1966) 706;  
C.G.Callan and B.Treiman *Phys.Rev.* **162** (1967) 1494
- [9] E.Golowich, Proc. Conf. CP–violation and Astrophysics, Chateau de Blois, France, May 1989
- [10] W.Bernreuther, J.P.Ma and T.Schröder, *Phys.Lett.***B297**(1992) 318  
T. Arens and L.M. Sehgal *Nucl. Phys.***B393** (1993) 46 and references therein
- [11] S.M.Bilenky, E.Christova, N.Nedelcheva, *Bulg.J.Phys.***13** (1986) 283

- [12] J.P.Ma, A.Brandenburg, *Z.Phys* **C56** (1992) 97
- [13] M.Dugan, B.Grinshtein, L.Hall *Nucl.Phys.* **B255** (1985) 413  
W.Bernreuter, M.Suzuki *Rev.Mod.Phys.* **63** (1991) 313



## Figure Captions

- Fig. 1:** Diagrams inducing CP violation in top production and decay.
- Fig. 2:** The imaginary parts of the dipole moments  $\Im md^\gamma$  and  $\Im md^Z$  as a function of (a)  $\sqrt{s}/2$ , (b)  $m_{\tilde{g}}$ , and (c)  $m_{\tilde{t}_1}$ , for  $m_t = 175$  GeV,  $m_{\tilde{t}_2} = 400$  GeV,  $m_{\tilde{b}_L} = 200$  GeV. We have taken  $\sqrt{s} = 500$  GeV in (b) and (c),  $m_{\tilde{g}} = 200$  GeV in (a) and (c),  $m_{\tilde{t}_1} = 150$  GeV in (a) and (b).
- Fig. 3:**  $\Im mg_R$  as a function of (a)  $m_{\tilde{g}}$ , and (b)  $m_{\tilde{b}_L}$ , for  $\sqrt{s} = 500$  GeV,  $m_t = 175$  GeV,  $m_{\tilde{t}_1} = 150$  GeV,  $m_{\tilde{t}_2} = 400$  GeV, with  $m_{\tilde{b}_L} = 200$  GeV in (a) and  $m_{\tilde{g}} = 200$  GeV in (b).
- Fig. 4:** The CP violating contribution to the observables  $M_i$ ,  $i = 1, \dots, 4$ , as a function of (a)  $\sqrt{s}$ , (b)  $m_{\tilde{g}}$ , and (c)  $m_{\tilde{t}_1}$ , for  $m_t = 175$  GeV,  $m_{\tilde{t}_2} = 400$  GeV,  $m_{\tilde{b}_L} = 200$  GeV. We have taken  $\sqrt{s} = 500$  GeV in (b) and (c),  $m_{\tilde{g}} = 200$  GeV in (a) and (c),  $m_{\tilde{t}_1} = 150$  GeV in (a) and (b).  $M_1$ (full line),  $M_2$ (long-dashed),  $M_3$ (short-dashed),  $M_4$ (dashed-dotted).
- Fig. 5:** The CP violating contribution to the asymmetries  $O_i$ ,  $i = 1, \dots, 4$ , as a function of (a)  $\sqrt{s}$ , (b)  $m_{\tilde{g}}$ , and (c)  $m_{\tilde{t}_1}$ , for  $m_t = 175$  GeV,  $m_{\tilde{t}_2} = 400$  GeV,  $m_{\tilde{b}_L} = 200$  GeV. We have taken  $\sqrt{s} = 500$  GeV in (b) and (c),  $m_{\tilde{g}} = 200$  GeV in (a) and (c),  $m_{\tilde{t}_1} = 150$  GeV in (a) and (b).  $O_1$ (full line),  $O_2$ (long-dashed),  $O_3$ (short-dashed),  $O_4$ (dashed-dotted).

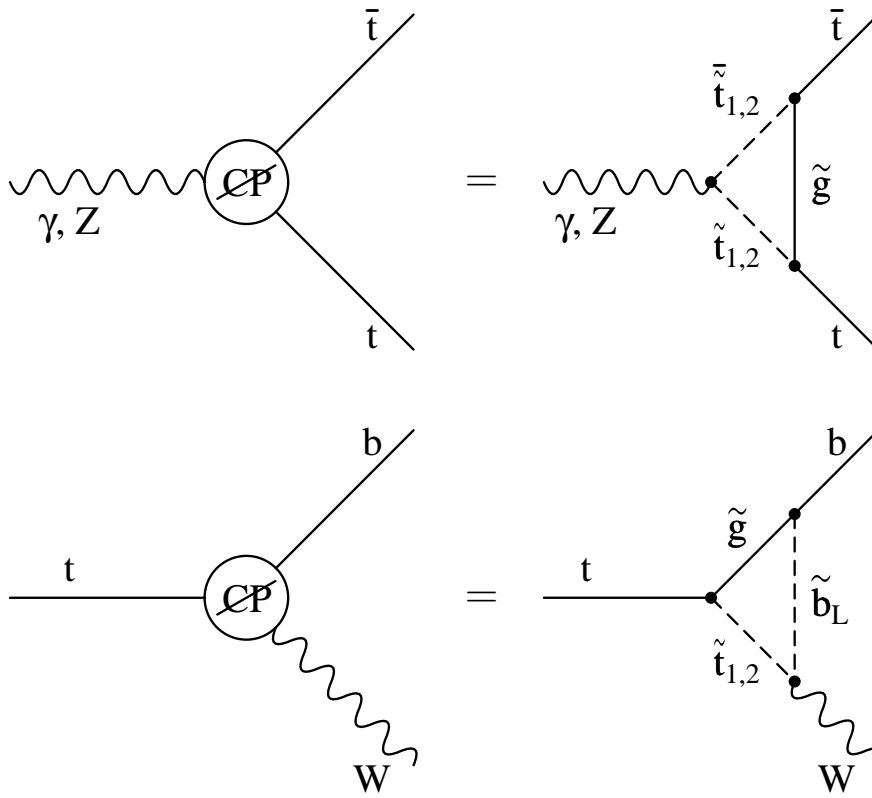
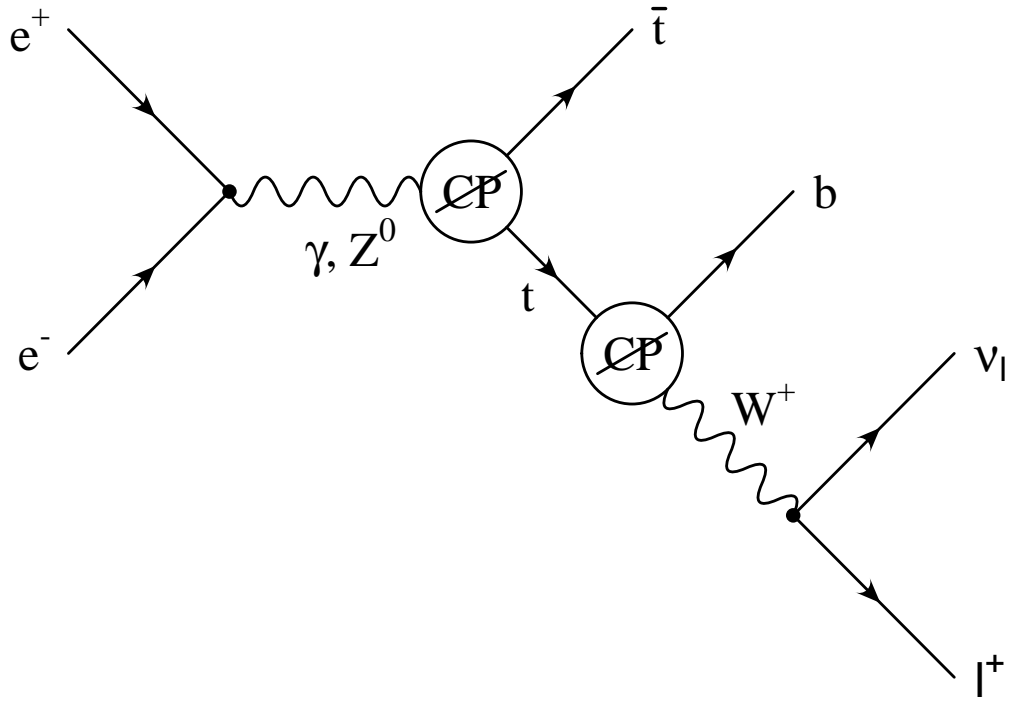
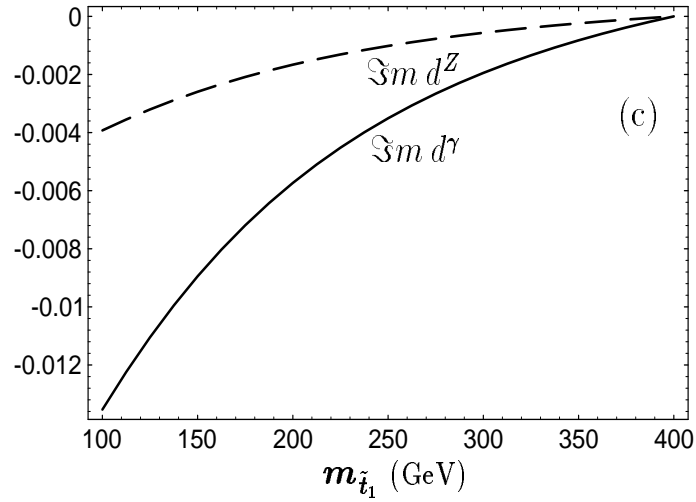
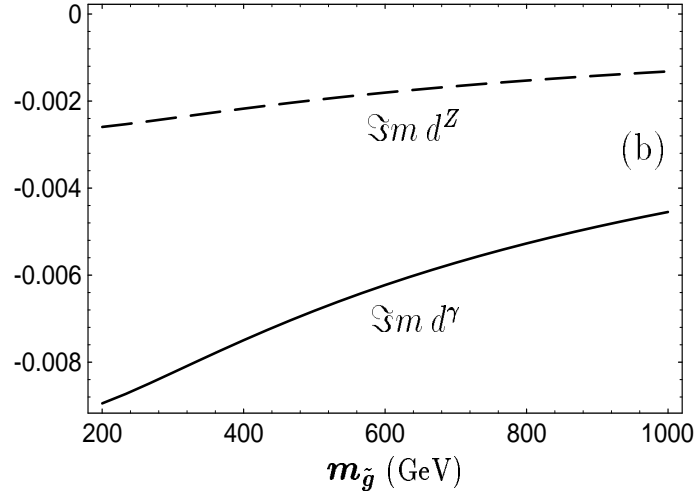
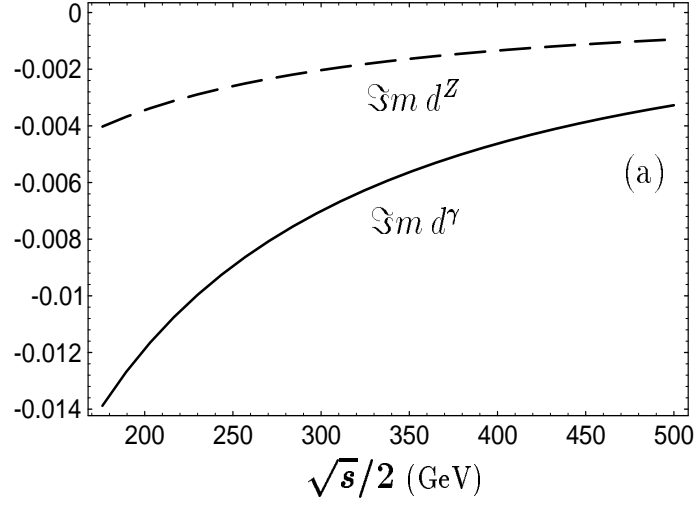
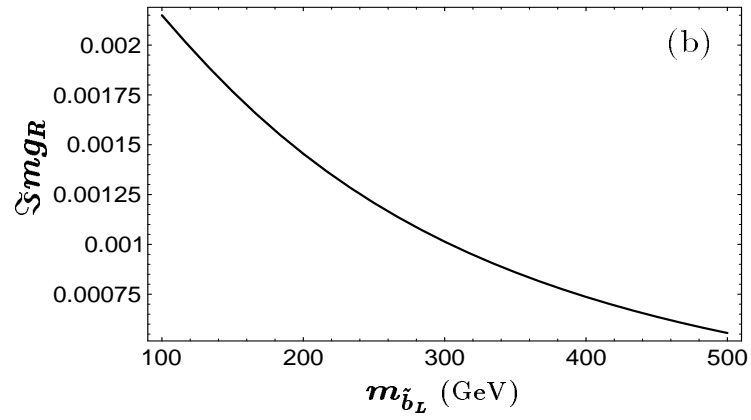
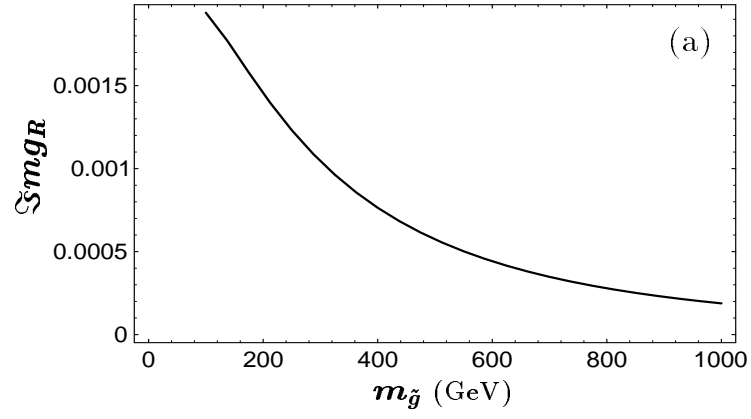


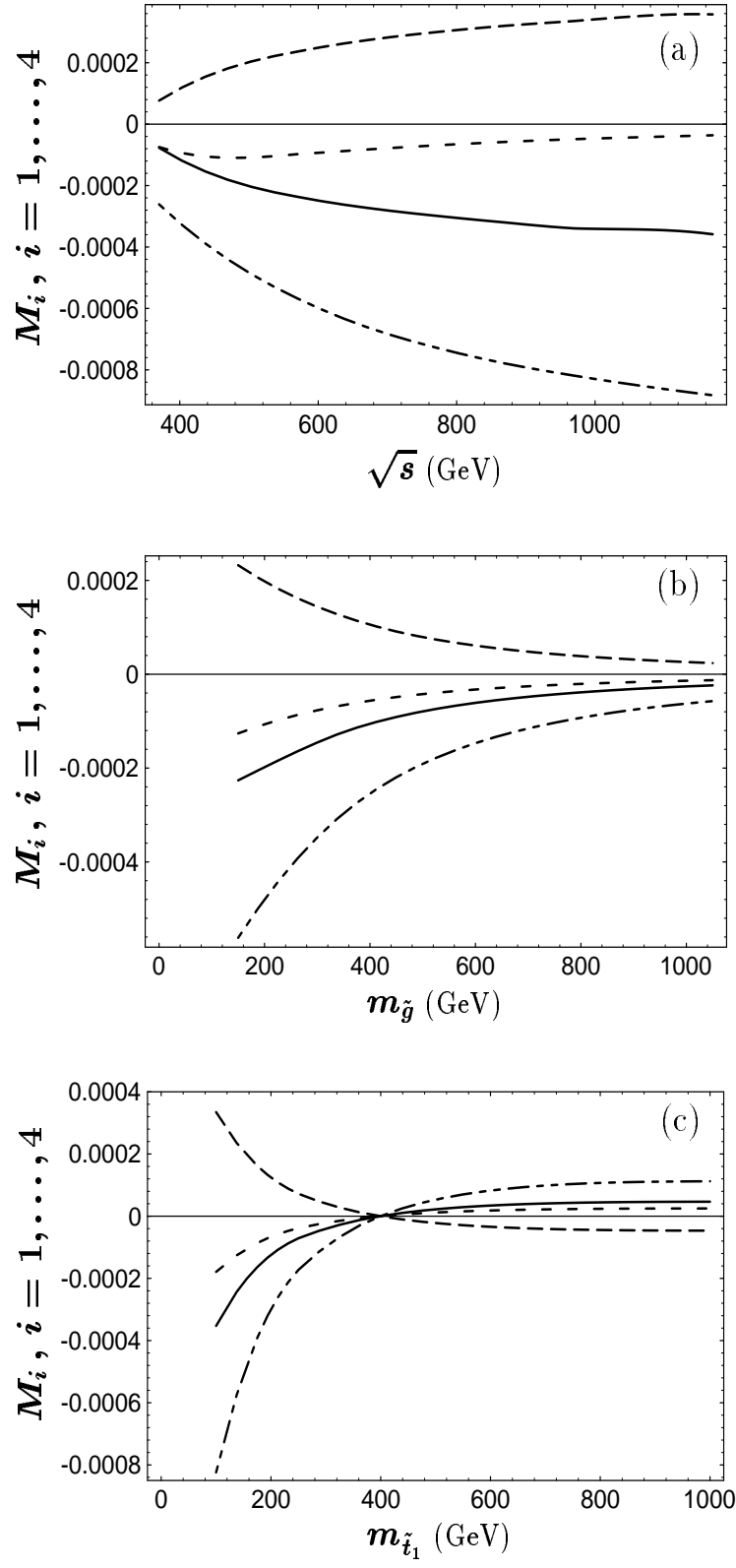
Figure 1



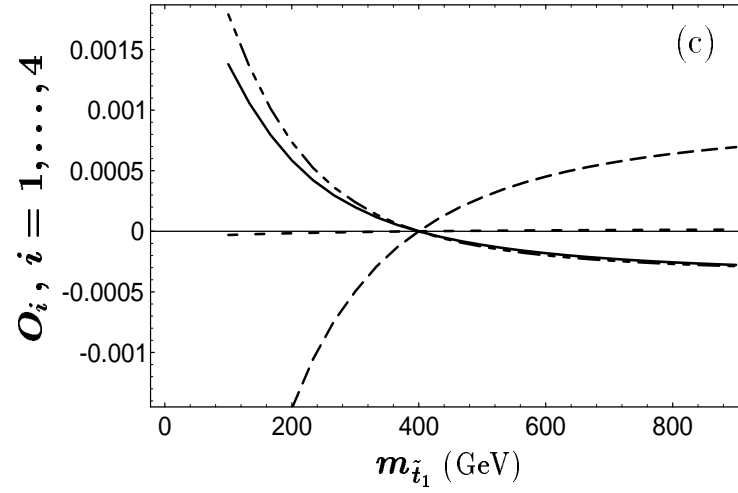
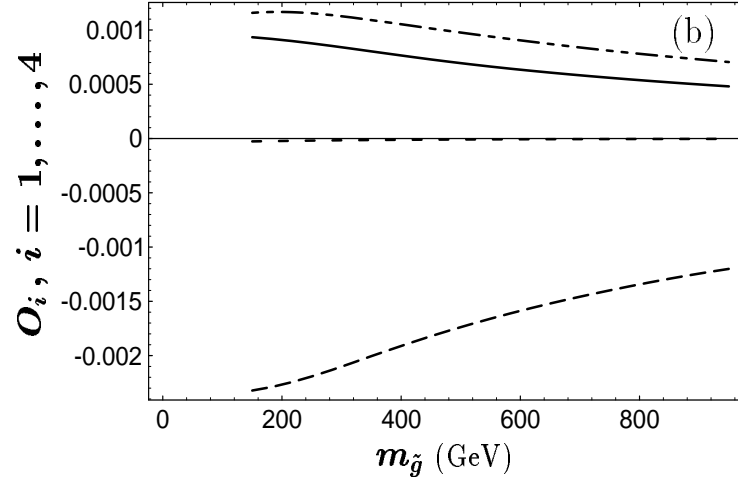
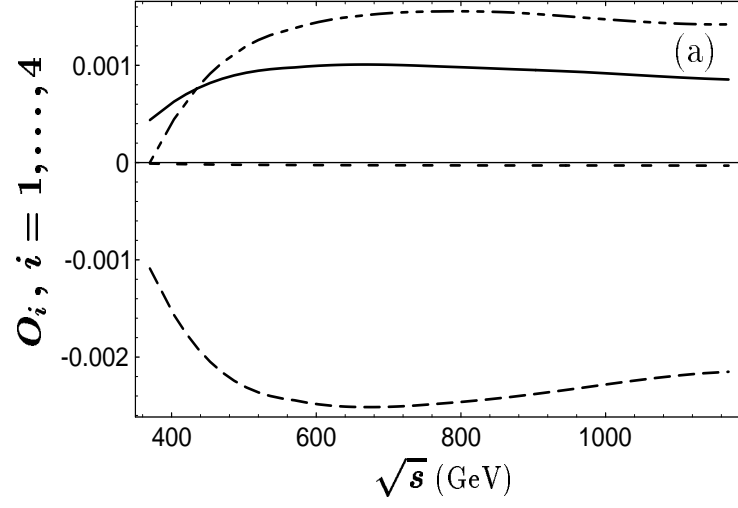
**Figure 2**



**Figure 3**



**Figure 4**



**Figure 5**